

Supplementary Information

Tree height and leaf drought tolerance traits shape growth responses across droughts in a temperate broadleaf forest

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Appendix S1. Further Package Citations

Table S1. Monthly Palmer Drought Severity Index (PDSI), and its rank among all years between 1950 and 2009 (driest=1), for focal droughts.

year	month	PDSI	rank
1966	May	-2.98	2
	June	-3.40	2
	July	-4.08	2
	August	-4.82	1
1977	May	-2.96	3
	June	-3.28	3
	July	-3.61	3
	August	-3.68	3
1999	May	-3.63	1
	June	-4.21	1
	July	-4.53	1
	August	-4.64	2

Table S2. Species-specific bark thickness regression equations

Species	Equations	R^2
Carya cordiformis	$\ln[B] = -1.56 + 0.416 \cdot \ln[DBH]$	0.226
Carya glabra	$\ln[B] = -0.393 + 0.268 \cdot \ln[DBH]$	0.040
Carya ovalis	$\ln[B] = -2.18 + 0.651 \cdot \ln[DBH]$	0.389
Carya tomentosa	$\ln[B] = -0.477 + 0.301 \cdot \ln[DBH]$	0.297
Fagus grandifolia	$\ln[B] = 1 \cdot \ln[DBH]$	
Fraxinus americana	$\ln[B] = 0.418 + 0.268 \cdot \ln[DBH]$	0.256
Juglans nigra	$\ln[B] = 0.346 + 0.279 \cdot \ln[DBH]$	0.246
Liriodendron tulipifera	$\ln[B] = -1.14 + 0.463 \cdot \ln[DBH]$	0.545
Quercus alba	$\ln[B] = -2.09 + 0.637 \cdot \ln[DBH]$	0.603
Quercus prinus	$\ln[B] = -1.31 + 0.528 \cdot \ln[DBH]$	0.577
Quercus rubra	$\ln[B] = -0.593 + 0.292 \cdot \ln[DBH]$	0.087

Table S3. Species-specific height regression equations

Species	Equations	R^2
Carya cordiformis	$\ln[H] = 0.332 + 0.808 * \ln[DBH]$	0.874
Carya glabra	$\ln[H] = 0.685 + 0.691 * \ln[DBH]$	0.841
Carya ovalis	$\ln[H] = 0.533 + 0.741 * \ln[DBH]$	0.924
Carya tomentosa	$\ln[H] = 0.726 + 0.713 * \ln[DBH]$	0.897
Fagus grandifolia	$\ln[H] = 0.708 + 0.662 * \ln[DBH]$	0.857
Liriodendron tulipifera	$\ln[H] = 1.33 + 0.52 * \ln[DBH]$	0.771
Quercus alba	$\ln[H] = 0.74 + 0.645 * \ln[DBH]$	0.719
Quercus prinus	$\ln[H] = 0.41 + 0.757 * \ln[DBH]$	0.886
Quercus rubra	$\ln[H] = 1.00 + 0.574 * \ln[DBH]$	0.755
all	$\ln[H] = 0.839 + 0.642 * \ln[DBH]$	0.857

Table S4. Individual tests of species traits as drivers of drought resistance, where Rt is used as the response variable.

variable	category	all droughts		1966		1977		1999	
		$\Delta AICc$	coefficients	$\Delta AICc$	coefficients	$\Delta AICc$	coefficients	$\Delta AICc$	coefficients
xylem porosity	R	-0.80	0.0630	2.29**	0.190	1.92*	-0.152	3.36**	0.1500
	D/SR		0.0000		0.000		0.000		0.0000
<i>PLA</i>		6.70	-0.0140	9.13**	-0.025	-0.32	-0.010	-0.95	-0.0070
<i>LMA</i>		-2.01	0.0002	-1.9	0.001	-1.68	-0.002	-2.03	0.0003
π_{ulp}		1.33	-0.1740	-1.65	-0.107	1.23*	-0.245	-0.1	-0.1690
<i>WD</i>		-1.97	-0.0310	-1.26	-0.206	-1.44	-0.154	0.66	0.2720

Variable abbreviations are as in Table 2. $\Delta AICc$ is the $AICc$ of a model excluding the trait minus that of the model including it.

* $\Delta AICc > 1$: variable meets $\Delta AICc$ criterion for inclusion in full model

** $\Delta AICc > 2$: variable is considered significant as an individual predictor (and meets $\Delta AICc$ criterion for inclusion in full model)

Table S5. Individual tests of species traits as drivers of drought resistance, where Rt_{ARIMA} is used as the response variable.

variable	category	all droughts		1966		1977		1999	
		$\Delta AICc$	coefficients	$\Delta AICc$	coefficients	$\Delta AICc$	coefficients	$\Delta AICc$	coefficients
xylem porosity	R	-1.47	0.0420	0.95	0.1520	2.84**	-0.171	2.27**	0.155
	D/SR		0.0000		0.0000		0.000		0.000
<i>PLA</i>		4.48**	-0.0120	10.15**	-0.0240	-0.9	-0.008	-1.67	-0.005
<i>LMA</i>		-1.99	-0.0003	-2.02	0.0005	-0.42	-0.003	-1.9	0.001
π_{tlp}		0.42	-0.1510	-1.94	-0.0530	-0.53	-0.179	0.04	-0.200
<i>WD</i>		-1.94	-0.0390	-0.08	-0.3040	-1.57	-0.142	0.83	0.316

Variable abbreviations are as in Table 2. $\Delta AICc$ is the AICc of a model excluding the trait minus that of the model including it.

** $\Delta AICc > 2$: variable considered significant as an individual predictor

Table S6. Individual tests of species traits as drivers of drought recovery (Re).

variable	category	all droughts		1966		1977		1999	
		$\Delta AICc$	coefficients	$\Delta AICc$	coefficients	$\Delta AICc$	coefficients	$\Delta AICc$	coefficients
xylem porosity	R	15.25**	-0.280	9.9**	-0.474	-1.67	-0.0370	17.06**	-0.3380
	D/SR		0.000		0.000		0.0000		0.0000
PLA		-1.98	0.002	-1.33	0.014	1.1*	-0.0090	-2.03	0.0010
LMA		-1.35	-0.002	0.32	-0.008	-2.04	-0.0001	-2.03	-0.0005
π_{tlp}		-1.13	-0.149	-1.94	-0.101	1.08*	-0.1630	-1.14	-0.2020
WD		-1.86	-0.088	-1.6	0.278	-1.68	-0.0980	-1.03	-0.2950

Variable abbreviations are as in Table 2. $\Delta AICc$ is the $AICc$ of a model excluding the trait minus that of the model including it.

** $\Delta AICc > 2$: variable considered significant as an individual predictor

Table S7. Individual tests of species traits as drivers of drought resilience (R_s).

variable	category	all droughts		1966		1977		1999	
		ΔAICc	coefficients	ΔAICc	coefficients	ΔAICc	coefficients	ΔAICc	coefficients
xylem porosity	R	0.24	-0.147	-1.29	-0.110	1.42*	-0.263	-1.11	-0.0840
	D/SR		0.000		0.000		0.000		0.0000
<i>PLA</i>		1.09*	-0.016	1.09*	-0.020	-0.51	-0.017	0.67	-0.0130
<i>LMA</i>		-1.9	-0.001	-1	-0.004	-1.95	-0.001	-2.02	-0.0004
π_{tlp}		2.5**	-0.347	-1.11	-0.212	1.57*	-0.468	6.11**	-0.3730
<i>WD</i>		-1.83	-0.109	-2.05	-0.020	-1.37	-0.298	-2.02	0.0360

Variable abbreviations are as in Table 2. ΔAICc is the AICc of a model excluding the trait minus that of the model including it.

** $\Delta\text{AICc} > 2$: variable considered significant as an individual predictor

Table S8. Summary of top full models for each drought instance, where Rt is used as the response variable.

drought	$\Delta AICc$	$Marginal R^2$	$Conditional R^2$	Intercept	$\ln[H]$	$\ln[TWI]$	$\ln[H] * \ln[TWI]$	PLA	π_{up}
all	0.000	0.08	0.12	1.131	-0.057	-0.086	-	-0.012	-0.113
	0.583	0.06	0.11	1.423	-0.055	-0.086	-	-0.013	-
	0.726	0.08	0.12	1.537	-0.202	-0.326	0.082	-0.012	-0.114
	1.352	0.06	0.11	1.826	-0.198	-0.324	0.081	-0.013	-
1966	0.000	0.16	0.25	1.622	-0.135	-	-	-0.025	-
1977	0.000	0.06	0.22	0.503	-	-0.144	-	-	-0.24
	0.908	0.01	0.21	1.069	-	-0.144	-	-	-
	0.988	0.06	0.22	0.568	-0.03	-0.139	-	-	-0.246
	1.144	0.08	0.24	0.684	-	-0.142	-	-0.007	-0.204
	1.267	0.04	0.22	1.211	-	-0.141	-	-0.01	-
1999	0.000	0.01	0.18	1.061	-	-0.102	-	-	-
	0.023	0.04	0.19	0.659	-	-0.101	-	-	-0.169
	0.954	0.02	0.19	1.157	-	-0.1	-	-0.007	-
	1.513	0.05	0.21	0.783	-	-0.1	-	-0.005	-0.145
	1.803	0.01	0.18	1.024	0.013	-0.103	-	-	-
	1.901	0.04	0.19	0.635	0.011	-0.102	-	-	-0.166

Models are ranked by AICc. Shown are all models whose AICc value falls within 2.0 ($\Delta AICc < 1$) of the best model (bold). R^2 refers to conditional R^2 . Year was included in the model for all drought years, but its effect was not included in any top models, and coefficients were small (1966: 0, 1977: -0.019, 1999: -0.005; same values in all top models).

Table S9. Summary of top models for each drought instance, where Rt_{ARIMA} is used as the response variable.

drought	$\Delta AICc$	R^2	Intercept	$\ln[H]$	$\ln[TWI]$	$\ln[H] * \ln[TWI]$	PLA	π_{tlp}	$(1 sp)[novariables]$
all	0.000	0.09	1.125	-0.307	-0.506		0.140	-0.012	
	0.425	0.10	0.879	-0.310	-0.508		0.140	-0.011	-0.096
	1.208	0.09	0.424	-0.060	-0.100			-0.012	
	1.695	0.10	0.178	-0.061	-0.100			-0.011	-0.095
1966	0.000	0.23	1.660	-0.154			-0.024		
	1.393	0.23	1.735	-0.152	-0.047		-0.024		
	1.457	0.23	1.859	-0.152			-0.025	0.078	
1977	0.000	0.16	1.130		-0.180				
	0.424	0.16	2.453	-0.461	-0.896		0.250		
	0.688	0.17	0.720		-0.179				-0.173
	0.922	0.17	2.040	-0.466	-0.898		0.251		-0.180
	0.927	0.17	1.248		-0.177			-0.008	
	1.322	0.17	2.569	-0.461	-0.893		0.250	-0.008	
	1.709	0.15	1.183	-0.020	-0.177				
1999	0.000	0.20	0.563		-0.076			-0.200	
	0.064	0.19	0.421					-0.202	
	0.127	0.18	1.036		-0.077				
	0.256	0.18							0.899
	1.777	0.20	0.529	0.016	-0.078			-0.195	
	1.797	0.20	1.101		-0.076		-0.004		
	1.815	0.18	0.986	0.018	-0.079				
	1.838	0.20	0.972				-0.005		
	1.933	0.19	0.391	0.012				-0.199	
	1.979	0.21	0.612		-0.075		-0.002	-0.190	
	1.999	0.21	0.482				-0.002	-0.190	

Models are ranked by AICc. Shown are all models whose AICc value falls within 2.0 ($\Delta AICc < 1$) of the best model (bold). R^2 refers to conditional R^2 . Year was included in the model for all drought years, but its effect was not included in any top models, and coefficients were small (1966: 0, 1977: -0.03, 1999: 0.008; same values in all top models).

Table S10. Summary of top models for each drought instance, where R_c is used as the response variable.

drought	$\Delta AICc$	$Marginal R^2$	$Conditio' - lR^2$	Intercept	$\ln[H]$	$\ln[TWI]$	$\ln[H] * \ln[TWI]$	PLA	π_{up}	No variables
all	0.000	0.05	0.17	0.434	0.345	0.844	-0.269	-	-	-
	0.995	0.05	0.17	1.913	-0.126	-	-	-	-	-
	1.135	0.06	0.17	0.077	0.344	0.845	-0.269	-	-0.152	-
	1.991	0.05	0.18	0.41	0.346	0.843	-0.269	0.002	-	-
1966	0.000	0.01	0.28	-0.797	0.89	1.263	-0.475	-	-	-
	1.040	0.00	0.25	-	-	-	-	-	-	1.577
	1.367	0.02	0.30	-0.984	0.888	1.257	-0.474	0.013	-	-
	1.785	0.00	0.26	1.781	-	-0.114	-	-	-	-
	1.956	0.01	0.30	-1.025	0.89	1.261	-0.475	-	-0.097	-
1977	0.000	0.17	0.17	2.485	-0.482	-	-	-	-0.157	-
	0.299	0.17	0.17	2.943	-0.47	-	-	-0.008	-	-
	0.716	0.17	0.18	2.657	-0.477	-	-	-0.006	-0.114	-
	0.807	0.17	0.18	1.152	0.071	1.026	-0.308	-0.009	-	-
	0.875	0.17	0.18	2.729	-0.47	0.124	-	-0.009	-	-
	0.891	0.17	0.18	2.271	-0.479	0.115	-	-	-0.158	-
	0.910	0.17	0.18	0.712	0.054	1.004	-0.304	-	-0.159	-
	1.315	0.17	0.18	0.871	0.065	1.023	-0.308	-0.006	-0.112	-
	1.331	0.16	0.17	2.805	-0.464	-	-	-	-	-
	1.372	0.17	0.18	2.445	-0.475	0.122	-	-0.006	-0.112	-
	1.974	0.16	0.17	2.597	-0.466	0.118	-	-	-	-
1999	0.000	0.00	0.16	-	-	-	-	-	-	1.281
	0.532	0.00	0.17	1.093	-	0.105	-	-	-	-
	1.091	0.02	0.19	0.779	-	-	-	-	-0.212	-
	1.609	0.02	0.19	0.578	-	0.106	-	-	-0.217	-
	1.755	0.00	0.17	1.2	0.027	-	-	-	-	-
	1.996	0.00	0.18	1.251	-	-	-	0.002	-	-

Models are ranked by AICc. Shown are all models whose AICc value falls within 2.0 ($\Delta AICc < 1$) of the best model (bold). R^2 refers to conditional R^2 . Year was included in the model for all drought years, but its effect was not included in any top models, and coefficients were small (**1966: 0, 1977: -0.03, 1999: 0.008; same values in all top models**).

Table S11. Summary of top models for each drought instance, where R_s is used as the response variable.

drought	$\Delta AICc$	$Marginal R^2$	$Conditio' - lR^2$	Intercept	$\ln[H]$	$\ln[TWI]$	$\ln[H] * \ln[TWI]$	PLA	π_{tlp}	No variables
all	0.000	0.10	0.17	-0.265	0.348	0.864	-0.291	-0.012	-0.287	-
	0.176	0.08	0.16	-0.572	0.347	0.859	-0.291	-	-0.347	-
	1.518	0.07	0.16	0.458	0.354	0.866	-0.292	-0.016	-	-
	1.552	0.09	0.17	1.253	-0.166	-	-	-0.011	-0.288	-
	1.698	0.08	0.16	0.94	-0.166	-	-	-	-0.348	-
1966	0.000	0.04	0.15	1.834	-0.085	-	-	-0.02	-	-
	0.402	0.03	0.16	1.589	-	-	-	-0.02	-	-
	1.189	0.00	0.14	1.534	-0.082	-	-	-	-	-
	1.313	0.00	0.15	-	-	-	-	-	-	1.293
	1.692	0.04	0.16	1.534	-0.085	-	-	-0.018	-0.116	-
1977	0.000	0.14	0.28	-0.932	0.294	1.207	-0.384	-	-0.467	-
	0.497	0.13	0.28	1.194	-0.383	-	-	-	-0.469	-
	1.304	0.15	0.30	-0.648	0.294	1.208	-0.383	-0.011	-0.411	-
	1.542	0.13	0.28	1.026	-0.387	0.095	-	-	-0.472	-
	1.555	0.09	0.28	0.138	0.304	1.211	-0.385	-	-	-
	1.852	0.14	0.29	1.467	-0.381	-	-	-0.01	-0.416	-
1999	0.000	0.07	0.13	0.237	-	-	-	-	-0.366	-
	0.313	0.08	0.14	0.472	-	-	-	-0.008	-0.317	-
	0.503	0.07	0.13	0.358	-0.048	-	-	-	-0.376	-
	0.532	0.07	0.13	0.394	-	-0.086	-	-	-0.364	-
	0.726	0.09	0.14	0.588	-0.047	-	-	-0.008	-0.328	-
	1.079	0.09	0.15	0.602	-	-0.081	-	-0.008	-0.319	-
	1.249	0.07	0.13	0.495	-0.044	-0.08	-	-	-0.374	-
	1.706	0.09	0.14	0.699	-0.044	-0.075	-	-0.007	-0.329	-

Models are ranked by AICc. Shown are all models whose AICc value falls within 2.0 ($\Delta AICc < 1$) of the best model (bold). R^2 refers to conditional R^2 . Year was included in the model for all drought years, but its effect was not included in any top models, and coefficients were small (**1966: 0, 1977: -0.03, 1999: 0.008; same values in all top models**).

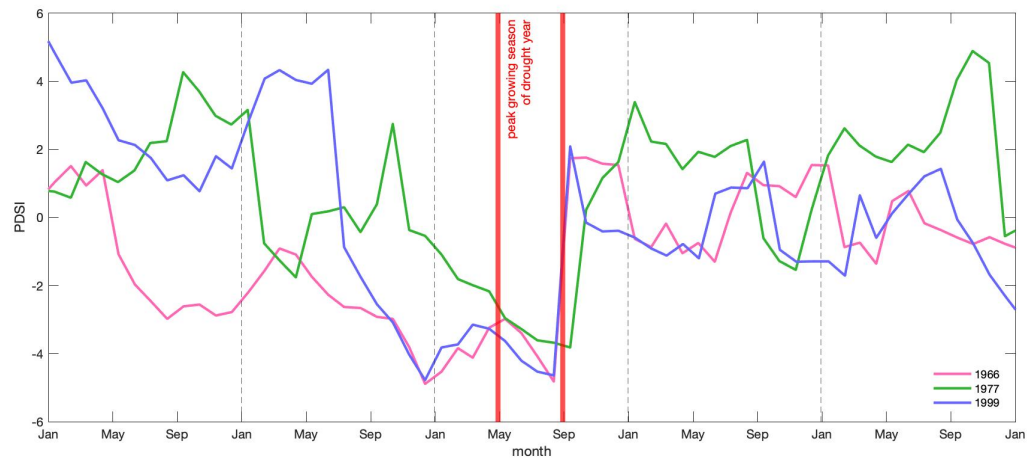


Figure S1. Time series of Palmer Drought Severity Index (PDSI) for each focal drought year ± 2 years

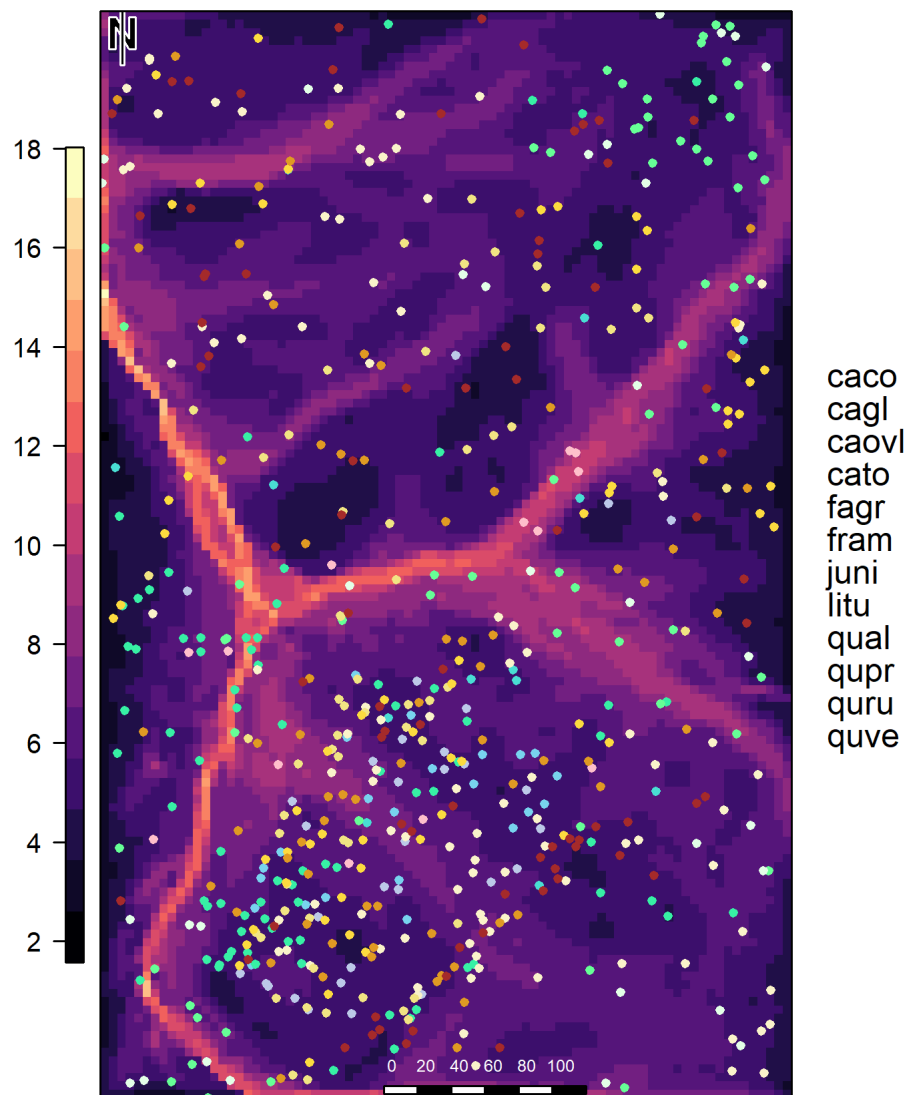


Figure S2. Map of ForestGEO plot showing topographic wetness index and location of cored trees. Scale units are in meters

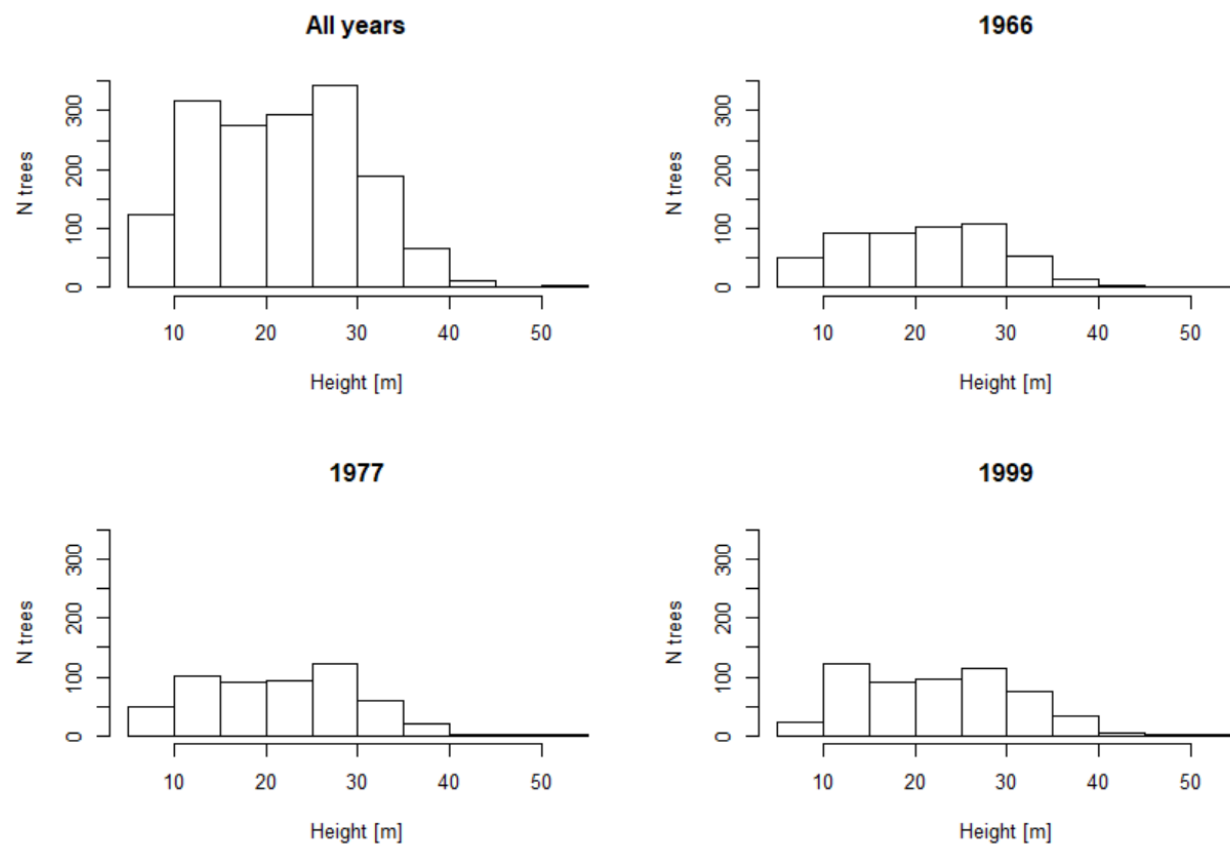


Figure S3. Distribution of reconstructed tree heights across drought years.

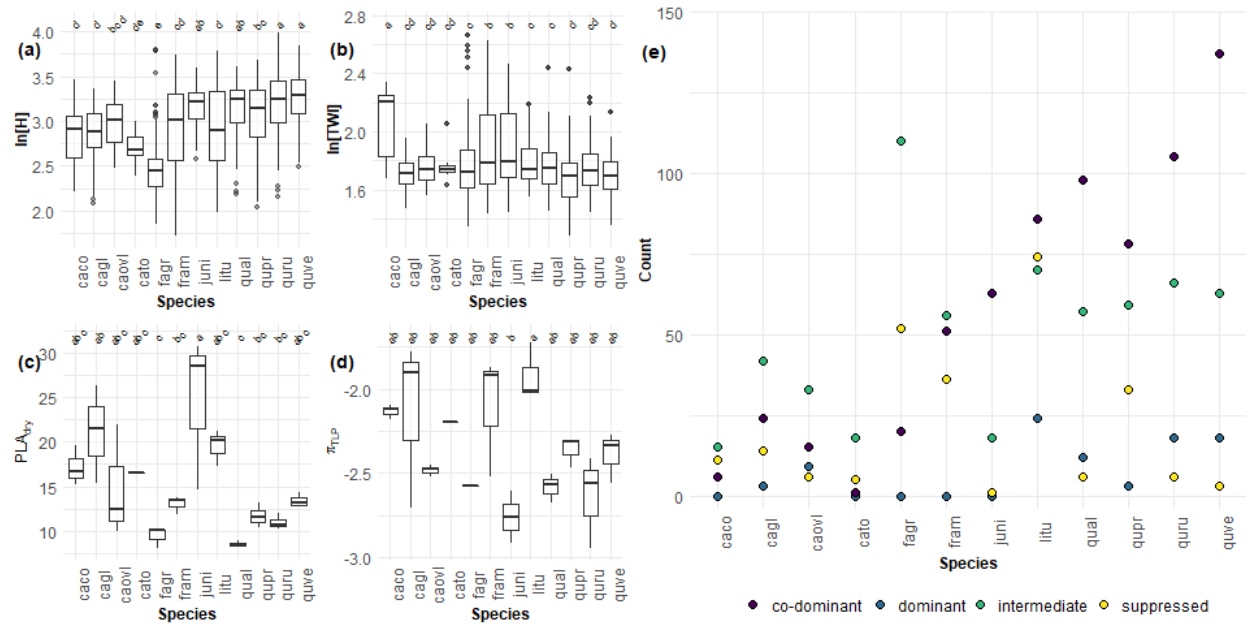


Figure S4. Distribution of independent variables by species. Species that are assigned the same letter are not significantly different from each other with regard to the tested variable.

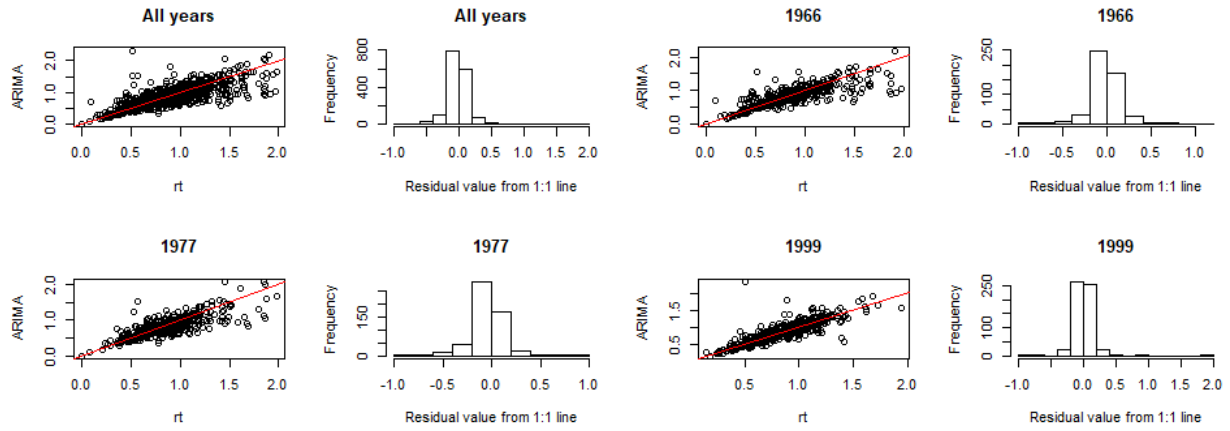


Figure S5. Comparison of R_t and R_{tARIMA} results, with residuals, for each drought scenario

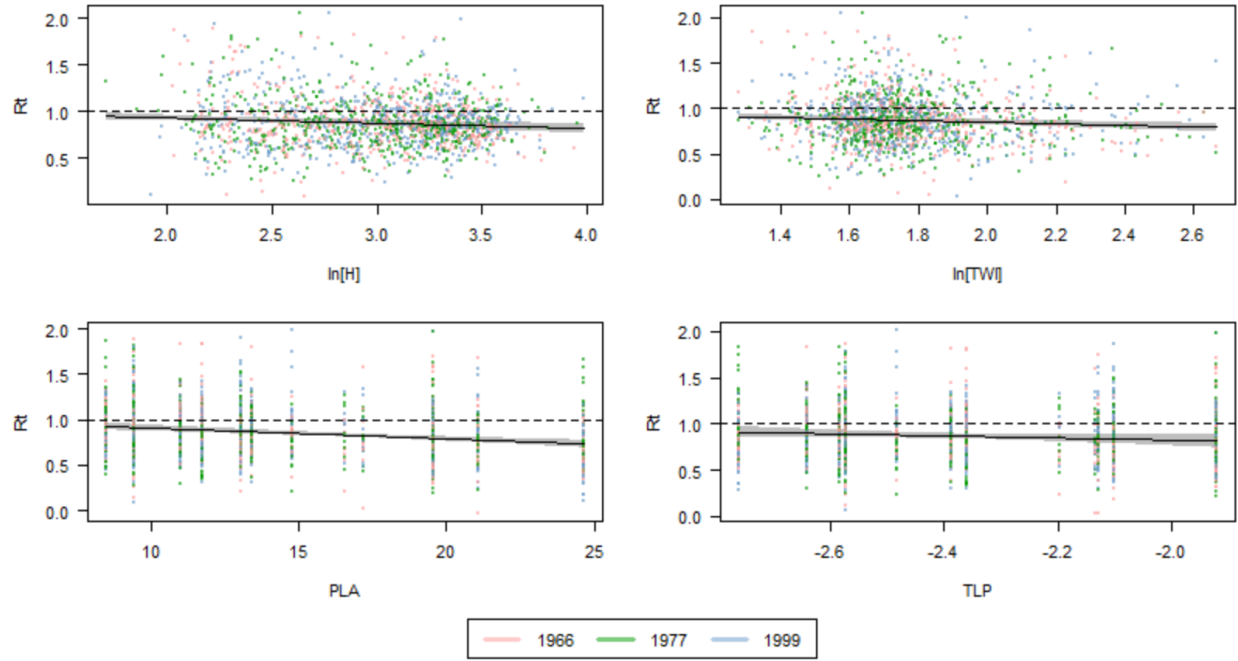


Figure S6. Visualization of the best model ($\Delta AICc=0$) with data for all droughts combined. Model coefficients are given in Table S6.

Appendix S1. Further Package Citations

While there were several R-packages we used for a specific purpose in our methods, numerous packages were immensely helpful for this research behind the scenes. As in all of science, this study is a representation of the work done by both the authors of this paper as well as countless others. While acknowledging everyone is impossible, we want to at least give thanks to those who made this work possible.

R-packages not already cited in the main manuscript include the following, listed alphabetically by corresponding package name:

(Urbanek, 2013; Winston Chang, 2014; Auguie, 2017; Wickham, 2017, 2019; Spinu *et al.*, 2018; Arnold, 2019; Barton, 2019; Bivand *et al.*, 2019; Bivand & Rundel, 2019; Bunn *et al.*, 2019; Dowle & Srinivasan, 2019; Fox *et al.*, 2019; Henry & Wickham, 2019; Lefcheck *et al.*, 2019; Perpinan Lamigueiro & Hijmans, 2019; R Core Team, 2019; Wickham & Bryan, 2019; Wickham *et al.*, 2019, 2020a,b; Wilke, 2019; Allaire *et al.*, 2020; Gagolewski *et al.*, 2020; Hijmans, 2020; Kassambara, 2020; Pebesma, 2020; Robinson & Hayes, 2020; Temple Lang, 2020; Wickham & Henry, 2020; Xie, 2020)

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